Product Improvement and Technological Tying: Vertical Product Differentiation

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Abstract

In a market for systems in which firms invest to improve their products, a monopoly supplier of a system component may have an incentive to advantage itself by technological tying; that is, by designing the component to work better in its own system. Consider a duopoly market structure in which the alternative systems consist of an essential component supplied by a monopolist (Firm 1) and a complementary component supplied by Firm 1 or a rival Firm 2. Each firm can invest in R&D to improve the quality of its system, but Firm 2 has a superior ability to supply a high quality system. A technological tie by Firm 1,however, degrades the quality of Firm 2's system. Consumers have identical preferences over vertically differentiated systems. If Firm 1 is unable to technologically tie, then there are multiple equilibria of the product improvement game in which the two firms compete on the quality and price of systems. There always exists an efficient pure strategy equilibrium in which Firm 2 improves its product optimally and captures the entire market. If quality advantage of Firm 2 is sufficiently small, then there also exists a second pure strategy equilibrium in which Firm 1's product improvement forecloses Firm 2. Under certain conditions, there also a mixed strategy equilibrium in which both firms invest with positive probability. In contrast, if Firm 1 can degrade the quality of Firm 2's system with a technological tie, and the wholesale price of the essential component is insufficiently remunerative, then there is a unique equilibrium outcome in which Firm 1 invests alone and forecloses its more efficient rival with an actual, or merely threatened, technological tie. A comparison of these equilibria for the two game forms demonstrates that a monopolist's ability to technologically tie can either increase or decrease social welfare.

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1 Introduction

Markets for systems feature production technologies that combine one or more component inputs to produce a final output. For example, information technology combines computer applications software with an operating system and hardware, voice telecommunications combines transport and switching with local exchange access, electricity service combines power generation with transmission and distribution, and so on. A monopoly supplier of an essential component of a system (such as an operating system, a local telephone exchange network, or an electricity transmission grid) could achieve a competitive advantage in the market for systems by granting itself superior technological access to the essential component. This could be accomplished by designing the essential component to work better with its own system, thereby degrading the performance of rival systems relative to its own. Such a "technological tie" can give the monopoly component supplier a greater incentive to innovate and may lead to a market structure *ex post* in which the integrated monopolist offers a superior system, even when the monopolist is a less capable producer of systems *ex ante*.[2]

The monopolist confronts a trade-off in considering the merits of a technological tie. On the one hand, by limiting rivals' technological access to an essential component, the monopolist profits by curtailing competition in the market for systems. On the other hand, the technological tie reduces the monopolist's ability to extract rents from more efficient rivals via sales of the essential component. If rivals have a superior ability to innovate, or produce systems that appeal to a large number of consumers, then by providing access, the monopolist profits from sales of the component as rivals expand their system sales. The technological tying trade-off depends on the price of the component. A high component price encourages the monopolist to provide efficient access to the essential component, while a low price encourages the monopolist to limit access with a technological tie. Therefore, technological tying is likely to be an attractive business strategy for the monopolist only if sales of the upstream component are insufficiently remunerative.

The traditional "Chicago School" emphasizes that there is no incentive for technological tying (other than for efficiency reasons) if a monopoly profit for the tying product can be extracted by charging a profit-maximizing price.[3] There may be reasons, however, why a monopolist has limited flexibility to charge rivals a profit-maximizing price for an essential component. For example, the

[2] A technological tie refers to the physical integration of a product with another product, in a manner that makes it costly for rivals to sell similar integrated products. A technological tie may also be accomplished by designing an interface or withholding technical information to impede the interoperability of a complementary product. See Lessig (2000) for a review of the case law on tying and its applicability to U.S. v. Microsoft.

[3] Bowman [1957] and Bork [1978], among others, maintain that the owner of an essential input that is used in fixed proportions with another competitively supplied good has no incentive to bundle the input and the complementary good or to tie purchase of the complementary good to the essential input. The argument is that there is a single monopoly profit, which the owner of the essential input can capture by charging a monopoly price.

component may have other uses, which consumers value differently. The monopolist may opt for a mixed bundling strategy, selling both systems and the component on a stand-alone basis, while imposing a technological tie to prevent arbitrage between the two.[4] Alternatively, regulation, including antitrust scrutiny, can constrain the price that can be charged for the essential input.

In light of these considerations, our analysis focus on tying incentives conditional on the price of the tying product. Consistent with the traditional view, we find that the ability to technological tie does not affect market outcomes when the price of the tying good is sufficiently high. Otherwise, a technological tie, or even the threat of a technological tie, can significantly impact market structure, prices, and innovation. In some cases, these impacts have negative welfare consequences; in other cases, the ability to impose a technological tie can increase social welfare.

Economides [1998a] shows that a price-regulated upstream monopolist participating in a downstream Cournot (quantity-setting) oligopoly has an incentive for non-price discrimination.[5] Our analysis expands on this observation by analyzing the incentives for and consequences of technological tying for product improvement in a downstream systems market where firms compete on quality and price.[6] In this paper, we consider the case of homogeneous consumer preferences over vertical differentiated products. In a companion paper, we consider heterogeneous consumers and horizontal product differentiation.

More specifically, we study markets for systems as duopoly games. Each of M consumers demands a system comprised of two components. Firm 1 offers a system comprised of one unit of component A and one unit of its version of component B. Firm 2 purchases component A from Firm 1 at a predetermined price w,[7] and offers consumers a system that consists of component A

[4]For example, suppose some consumers have willingnesses to pay of q_i for computer systems consisting of an operating system and application software, but other consumers would pay no more than w for a computer with e-mail and Internet browsing capability and have no demand for other applications. If there are enough consumers of the second type, Firm 1 would maximize profits by selling component A separately at price w, provided that it can prevent rivals or consumers from purchasing the operating system at the lower price and combining it with applications.

[5]In line with Chicago School reasoning, Bergman [2000] observes that no incentive for non-price discrimination exists if the input monopolist is a less efficient supplier of systems in the downstream market and the upstream price is profit-maximizing. See also Sibley and Weisman [1998] and Economides [2000].

[6]The new vertical foreclosure literature, which includes papers by Salop and Scheffman [1983], Krattenmaker and Salop [1986], Ordover, Salop and Scheffman [1990], Riordan and Salop [1995], and Riordan [2000], Hart and Tirole [ ], McAfee and Schwartz [ ], O'brien and Shafer [ ], and Rey and Tirole [ ] identify incentives for a firm that operates in both upstream and downstream markets to use price and exclusive contracts to influence downstream competition and to "raise rivals' costs". Our analysis can be interpreted as an exploration of technological tying as a raising rivals' costs strategy.

[7]We assume that Firm 1 is commited to the wholesale price w. Without such a commitment, Firm 2 would not invest, because of the ability Firm 1 to "hold up" Firm 2 by raising the wholesale price. Farrell and Katz [2000] reach a similar conclusion for an alternative timing in which the integrated firm prices the essential component after observing the realized qualities but before the prices of the competitively-supplied component.

and its version of component B.[8] In our basic "product innovation game," given wholesale price of component A, rival firms invest in quality improvements of component B, and subsequently compete on the price of systems. In the companion "technological tying game" there is also an intermediate stage in which Firm 1 can act to degrade the quality of Firm 2's system.

Given that consumers have homogeneous preferences, the market has a "winner take all" character, and multiple equilibria of the product improvement game are possible. There always exists an efficient pure strategy equilibrium in which Firm 2 improves its product optimally and captures the entire market. If the quality advantage of Firm 2 is sufficiently small, then there also exists an inefficient pure strategy equilibrium in which Firm 1 invests in product improvement and captures the market. In these equilibria, consumers enjoy a positive surplus as long as the losing firm imposes some competitive price pressure on the winner.

In the technological tying game, however, has a unique equilibrium outcome. If the wholesale price of the essential component is sufficiently remunerative, then Firm 1's ability to impose a technological tie is irrelevant, and the more efficient Firm 2 captures the market. Otherwise, Firm 1 imposes a technological tie that effectively forecloses its rival, and sets a price for its system that leaves consumers no surplus. In this case, technological tying distorts market structure and reduces consumer welfare by eliminating competition from Firm 2.[9]

There also can exist a realistic mixed strategy equilibrium in which each of the firms invests with positive probability. Possible mixed strategy equilibrium outcomes include one or the other firm investing alone, duplicative investments, an a complete failure to invest. In contrast, mixed strategy equilibria do not exist in the technological tying game. If the wholesale price is insufficiently remunerative, then Firm 1's unconstrained ability to impose a technological tying eliminates any incentive for product improvement by Firm 2. Surprisingly, technological tying improves social welfare compared to a mixes strategy equilibrium, even though consumers are worse off.

[8] While we assume that Firms 1 and 2 supply systems comprised of component A and firm-specific versions of component B, the analysis would be unchanged if consumers were to purchase product A from Firm 1 and combine A with B from Firm 1 or Firm 2. In this case component A can be an operating system (e.g. Microsoft Windows), and component B can be an application program, such as Microsoft Word or Wordperfect.

[9] Farrell and Katz [2000] also study the incentives for product innovation and technological tying in a market for vertical differentiated systems. In their "baseline" model, a monopoly supplies an essential component and competes with others to supply a complementary component. By "overinvesting" in product R&D for the complementary component, the integrated squeezes the rents of rival suppliers and is able to charge consumers more for the essential component; (see Bolton and Whinston [1993] for a related model of strategic overinvestment.) Moreover, the integrated firm has no incentive to disadvantage rivals with a technological tie. These results depend on their assumptions that (1) systems are assembled by consumers, and (2) the monopolist prices the essential component only after observing the qualities and prices of the competitively-supplied component. In constrast, we assume that firms supply systems directly to consumers and that the wholesale price of the essential component is determined prior to systems market competition.

2 Vertical Product Differentiation

The M consumers are identical in this model. Each consumer demands a system. The systems are differentiated in quality, which is partly exogenous and partly endogenous. A consumer's willingness-to-pay for a system consisting of components A and B from firm i is

$$q_i = \gamma_i + q(r_i), \tag{1}$$

where γ_i is an exogenous quality parameter specific to systems sold by Firm i, and the endogenous variable r_i is Firm i's investment in R&D to improve the quality of its system (or, equivalently, the quality of its component B). For analytical convenience, we assume that there are no additional variable costs of producing systems.

It is convenient to reinterpret (1) as firm i choosing a level of quality improvement

$$z_i = q_i - \gamma_i$$

by incurring an R&D cost

$$r_i = r(z_i).$$

We maintain several additional assumptions.

A1: The symmetric R&D cost function $r(z)$ is increasing, strictly convex, twice differentiable, and satisfies $r(0) = r'(0) = 0$.

The first assumption implies that there is a unique z^M that maximizes the net benefits from quality improvement $zM - r(z)$ and is the solution to $r'(z^M) = M$. Thus z^M is the efficient level of quality improvement for a firm selling to the entire market and $\pi^M \equiv z^M M - r(z^M) > 0$.

A2.: $\Gamma \equiv \gamma_2 - \gamma_1 > 0$.

The second assumption implies that Firm 2 is the more efficient supplier of systems for any level of investment in quality improvement.[10]

A3: $\pi^M > \Gamma M$.

The third assumption implies that Firm 1 can profitably leapfrog Firm 2's quality advantage by investing efficiently in product improvement. This assumption is not necessary for many of our results. We include it because it simplifies the exposition and describes an environment in which investment effects can dominate firm-specific efficiencies.

A4: $w \leq \bar{w}$, where $\bar{w} \equiv \gamma_2 + \pi^M/M$.

[10] This assumption is for interpretative purposes. The results, with straightforward modifications, hold for $\Gamma \leq 0$ also.

The fourth assumption simplifies by assuming that the wholesale price of component A lies below the monopoly level.[11] We make extensive use of $\bar{w}$ below. For reference, note that $\bar{w} > \gamma_1$ and $\bar{w} - \Gamma \geq \gamma_2$.

We begin by considering the quality improvements and the market shares that a social planner would choose to maximize total economic surplus. Let xM be the allocation of consumers to Firm 1 and $(1-x)M$ the allocation to Firm 2, and let z_1 and z_2 be the firms' investments in quality improvement. The social planner chooses (x, z_1, z_2) to maximize

$$W(x, z_1, z_2) = M\left[x\left(\gamma_1 + z_1\right) + (1-x)\left(\gamma_2 + z_2\right)\right] - r(z_1) - r(z_2).$$

The welfare optimum has $x = 0,\ z_1 = 0,$ and $z_2 = z^M$. Only the more efficient Firm 2 should invest in product improvement and supply systems.[12]

Next we turn to market-determined investments in product improvement.

3 Product Improvement Game: Pure Strategies

In this section we analyze the basic product improvement game with purely vertical product differentiation; the next section deals with technological tying. Let P_j be the price of a system from Firm j and let xM be Firm 1's sales of systems. Without loss of generality, we consider P_1 and P_2 such that all consumers purchase a system; i.e., the market is fully covered.[13] Hence Firm 2's sales are $(1-x)M$. If w is the price of component A, then the respective profits of the two firms are

$$\begin{aligned} \pi_1 &= (P_1 x + w(1-x))M - r(z_1) \\ &= (P_1 - w)Mx + wM - r(z_1) \end{aligned} \tag{2}$$

and

$$\pi_2 = (P_2 - w)M(1-x) - r(z_2). \tag{3}$$

Note as a consequence of full market coverage, w, the price of component A, is an opportunity cost of system sales for Firm 1 as well as a direct marginal cost for Firm 2.

Given w, competition proceeds in two stages. In the first stage, the firms simultaneously and independently choose a quality improvement z_i at cost $r(z_i)$.

[11] Maximized social surplus equals $\gamma_2 M + \pi^M$. This surplus is fully extracted by Firm 1 with a wholesale price equal to $\bar{w}$.

[12] The welfare optimum requires:

$$\begin{aligned} r'(z_1) &= Mx \\ r'(z_2) &= M(1-x) \\ z_1 - z_2 &\geq \Gamma \ \text{ if } x > 0, \end{aligned}$$

and the second-order conditions $\frac{dx}{dz_1}M - r''(z_1) \leq 0$ and $-\frac{dx}{dz_2}M - r''(z_2) \leq 0$. Clearly $W(0,0,z^M) > W(1,z^M,0)$. The convexity of $r(z)$ implies that $W(0,0,z^m) > W(x,z_1,z_2)$ for $x \in (0,1)$.

[13] Full market coverage requires $\max(q_1 - P_1, q_2 - P_2) \geq 0$, which is assured by profit maximization.

In the second stage, the firms simultaneously and independently set prices P_i after observing each other's quality. Consumers observe prices and qualities and choose the product that offers the greatest net utility. Consumers have identical preferences, so firm i makes sales to all M consumers if $q_i - P_i > \max(q_j - P_j, 0)$. When both products offer the same net utility, consumers choose the higher quality product. If both firms also have the same quality, then consumers are assumed to choose Firm 1. We restrict attention to subgame perfect Nash equilibria in pure strategies and ignore equilibria in which either firm prices below its marginal cost. We examine mixed strategies in the appendix.

Equilibrium prices and sales in the market for systems at stage two depend on the level of w and product qualities. Whichever firm has the higher quality system sells to the entire market at a price that may or may not be constrained by its rival. In each case, the firm that makes no sales sets a price equal to its opportunity cost w, which serves as a competitive check if the quality of its system is higher than w. For example, if $q_1 > q_2$, then Firm 2 sets price $P_2 = w$ and Firm 1 wins the market at price $P_1 = q_1 - q_2 + w$. If $q_1 > q_2$ and $q_2 < w$, then Firm 1 wins the market at price $P_1 = q_1$. A similar result holds for Firm 2 if $q_2 > q_1$ and $w < q_2$ because w is an opportunity cost of sales for Firm 1 and a direct cost for Firm 2. If $w \geq q_2$, then Firm 1 wins the market at price $P_1 = q_1$ even if $q_1 < q_2$.

Summarizing, Firm 1 sells to all M customers at a price $P_1 = q_1 - \max(q_2 - w, 0)$ if $q_1 \geq q_2$ or if $w \geq q_2$, and Firm 2 sells to all M customers at a price $P_2 = q_2 - \max(q_1 - w, 0)$ if $q_2 > q_1$ and $w < q_2$.

In stage 1 the firms invest in quality improvement anticipating the Bertrand-Nash equilibrium of the price subgame. It is immediate that both firms cannot make positive investments in a pure strategy equilibrium. One of the firms will capture the entire market, leaving the other firm better off not investing.

Proposition 1 *There does not exist an equilibrium in which both firms make positive investments. Thus, either* $z_1 = 0$ *or* $z_2 = 0$ *in equilibrium.*

Given our maintained assumptions there always exists an efficient pure strategy equilibrium in which Firm 2 captures the entire market. This an the efficient equilibrium because Firm 2 has an exogenous quality advantage.

Proposition 2 *There exists a equilibrium in which Firm 2 invests efficiently* ($z_2 = z^M$) *and Firm 1 does not invest in quality improvement* ($z_1 = 0$)*. Firm 2 sets a price equal to* $P_2 = \gamma_2 + z^M - \max(\gamma_1 - w, 0)$*, sells systems to all* M *customers, and earns* $\pi_2 = [\bar{w} - w - \max(\gamma_1 - w, 0)]M \geq 0$*. Firm 1 sets price* $P_1 = w$*, sells* M *units of component A and no systems, and earns* $\pi_1 = wM$*.*

Proof. Suppose Firm 1 deviates from the assumed equilibrium by investing $z_1 > 0$. This cannot be profitable unless Firm 1 can win the market from Firm 2, which requires $z_1 \geq ¢ z^M + \Gamma$. The best deviation for Firm 1 maximizes $\pi_1 = z_1 - z^M - \Gamma + w \; M - r(z_1)$ subject to this constraint. Convexity of $r(z)$ implies that the constraint binds and Firm 1's maximum deviation profit is $\pi_1 = wM - r(z^M + \Gamma) < wM$. Thus Firm 1 earns less profit by deviating from

$z_1 = 0$. Given that Firm 1 chooses $z_1 = 0$, the profit-maximizing investment for Firm 2 is $z_2 = z^M$. Firm 2's profit is $\pi_2 = [\bar{w} - w - \max(\gamma_1 - w, 0)]M$. ■

In the efficient equilibrium, Firm 1 is effectively foreclosed from competing with Firm 2 if $w > \gamma_1$. Firm 2's profit in this case is the maximum surplus $\bar{w}M$, less its payments to Firm 1 for component A. Firm 2's profit is independent of w for $w \leq \gamma_1$. In this range, Firm 1 exercises a competitive constraint on Firm 2's pricing equal to $\gamma_1 - w$, so Firm 2's net profit is $[\bar{w} - \gamma_1]M$.

Firm 1 does not profit by investing in quality improvement if it expects Firm 2 to do so. However, there may exist an alternative equilibrium in which only Firm 1 invests in product improvement. By assumption, Firm 1 can profitably leapfrog Firm 2's initial quality advantage by investing efficiently. Moreover, if $r(z^M) \geq \Gamma M$, then Firm 2 cannot profitably leapfrog Firm 1's post-investment product quality.

Proposition 3 *There exists a pure strategy equilibrium in which Firm 1 invests efficiently and Firm 2 does not invest if and only if* $r(z^M) \geq \Gamma M$. *Firm 1 sets price* $P_1 = \gamma_1 + z^M - \max(\gamma_2 - w, 0)$, *sells systems to all* M *customers, and earns* $\pi_1 = [\bar{w} - \Gamma - \max(\gamma_2 - w, 0)]M \geq 0$. *Firm 2 sets price* $P_2 = w$, *sells no systems, and earns* $\pi_2 = 0$.

Proof. If $z_1 = z^M$ and $z_2 = 0$, Firm 1 will make all sales at a price equal to $P_1 = \gamma_1 + z^M - \max(\gamma_2 - w, 0)$. If $w \leq \gamma_2$, then $P_1 = z^M - \Gamma + w$ and Firm 1 earns a profit equal to $\pi_1 = \pi^M - \Gamma M + wM \geq wM$ given the "leapfrogging" assumption A3. Furthermore, Firm 1 has no incentive to deviate and earn $\pi_1 = wM$ by choosing $z_1 = 0$, and Firm 1 has no incentive to choose any other level of quality improvement. If it is profitable for Firm 2 to deviate, then Firm 2 would choose z^M and earn $\pi_2 = \Gamma M - r(z^M)$. Therefore, Firm 2 has no incentive to deviate if $\Gamma M - r(z^M) \leq 0$. If $w > \gamma_2$, then $P_1 = \gamma_1 + z^M$ and Firm 1 earns an equilibrium profit equal to $\pi_1 = [\bar{w} - \Gamma]M$. If Firm 1 were to deviate and choose $z_1 = 0$, then Firm 1 would earn only $\gamma_1 M$ (because Firm 2 is foreclosed by $w > \gamma_2$). Thus Firm 1 has no incentive to deviate. Firm 2 has no incentive to deviate by the same reasoning as before. ■

In an equilibrium in which only Firm 1 invests, Firm 2 is foreclosed even though it is able to produce systems more efficiently *ex ante*. Such foreclosure can occur for any price of component A for suitable parameter values. By improving its system, Firm 1 endogenously becomes such a formidable competitor that Firm 2 cannot effectively compete.

There are multiple equilibria for a wide range of parameter configurations and the firms have divergent preferences when multiple equilibria coexist. Clearly, Firm 2 always prefers the socially efficient equilibrium in which it improves its product and captures the entire market. Firm 1 agrees with this preference only if the price of component A is sufficiently remunerative; i.e., if $w \geq \bar{w} - \Gamma$. Otherwise, if multiple equilibria exist, then Firm 1 prefers the socially inefficient equilibrium in which it improves its product and captures the market. This disagreement is important for understanding Firm 1's incentives for technological tying.

How do consumers fare in the different equilibria? The surplus that each consumer enjoys from the purchase of system i is

$$CS_i = q_i - P_i.$$

The equilibrium price of system i, when $q_i > q_j$ is $P_i = q_i - \max(q_j - w; 0)$. Therefore, in the efficient equilibrium when Firm 2 invests, the consumer surplus is $CS_2 = \max(\gamma_1 - w; 0)$. In the inefficient equilibrium when Firm 1 invests, the consumer surplus is $CS_1 = \max(\gamma_2 - w; 0)$. Thus we have the following result.

Corollary 4 *When multiple equilibria exist, consumer surplus is weakly higher in the socially inefficient equilibrium, and strictly higher when* $w < \gamma_2$.

With Bertrand competition, the equilibrium price is the quality level of the investing firm less the margin between quality and cost for the rival firm. This margin determines the net consumer surplus. The margin is larger for Firm 2 because Firm 2's quality level exceeds Firm 1's when neither firm invests. Firm 2 is a greater competitive threat to Firm 1 in the inefficient equilibrium than Firm 1 is to Firm 2 in the efficient equilibrium. Consumers benefit directly from the greater competitive threat of Firm 2 in the inefficient equilibrium.

4 Technological Tying Game

Firm 1 can avoid competition from Firm 2 by foreclosing Firm 2's access to component A, which we assume is available only from Firm 1. It conceivably might do this by contractually conditioning the purchase of A on the purchase of its component B, by selling a system consisting of components A and B and refraining from selling A separately (a pure bundling strategy), by charging a price for component A that is so high that Firm 2 cannot compete (or, equivalently, refusing to sell component A), or by designing component A so that a system performs worse when used with Firm 2's component B. This last strategy is a technological tie. A technological tie lowers the quality of a system made with component B from Firm 2 by an amount δ. That is, $q_2 = \gamma_2 + z_2 - \delta$ and q_1 is unchanged by the tie at $\gamma_1 + z_1$. A technological tie forecloses competition if δ is sufficiently large.

Foreclosure strategies that are based on a contractual tie, pure system sales, or refusals to deal in the upstream product may be ineffective if there is a separate demand for component A that the upstream monopolist wishes to serve. In contrast, a technological tie, which obstructs the ability of Firm 2 to offer a competitive system product, or makes it expensive for consumers to assemble a system using component B from Firm 2, does not limit the ability of the upstream monopolist to pursue a mixed bundling strategy in which the firm both sells systems and makes separate sales of component A in a different market. Furthermore, a technological tie allows the firm to finely tune the balance between the profits from component sales to a more efficient competitor and the benefits from limiting competition for its system sales. For simplicity, we assume that technological tying is costless for Firm 1 (other than the indirect cost of lost revenues from sales of component A to Firm 2) and thus consider only the incentives of Firm 1 to engage in this activity. Foreclosure is clearly inefficient because it eliminates competition from a more efficient producer. Nonetheless, Firm 1 may profit by foreclosing production by Firm 2 under some circumstances.

Consider the following three-stage "technological tying game", which amends the basic product improvement game studied in the previous subsection. In stage one, the firms choose costly quality improvements z_i as before. In stage two, Firm 1 is able to impose a technological tie that degrades Firm 2's quality by an amount $\delta \geq 0$. In stage three, the firms set prices $P_i \geq w$ as before.

With vertical product differentiation, Firm 1 may profit by degrading Firm 2's quality only if Firm 1 wins the system competition; i.e., only if $q_1 > q_2 - \delta$. Because Firm 1's profits are weakly increasing in δ, it is sufficient to focus on technological tying strategies that foreclose Firm 2 from the market. The following proposition summarizes the equilibria of the game with technological tying. We report the results conditional on the exogenous component price w. This reflects the importance of w for determining the costs and benefits from tying and is consistent with our assumption that w is determined by factors such as the value of mixed bundling for price discrimination, which we do not explicitly model.

Proposition 5 *In the technological tying game:*

(i) There exists an equilibrium in which Firm 1 invests efficiently, Firm 2 does not invest, and Firm 1 forecloses Firm 2 with a technological tie. In this equilibrium, Firm 1 sets $P_1 = \gamma_1 + z^M$*, sells systems to the entire market, and earns* $\pi_1 = [\bar{w} - \Gamma]M$ *. Firm 2 sets* $P_2 = w$ *and earns* $\pi_2 = 0$.

(ii) If $w \geq \bar{w} - \Gamma$*, then there is an equilibrium in which Firm 2 invests efficiently and Firm 1 does not invest. Firm 1 does not impose a technological tie. Firm 2 sets* $P_2 = \gamma_2 + z^M$*, sells systems to the entire market, and earns* $\pi_2 = [\bar{w} - w]M$*. Firm 1 sets* $P_1 = w$ *and earns* $\pi_1 = wM$*.*

(ii) If $w \geq \gamma_2$*, then there exists an equilibrium in which Firm 1 invests efficiently and Firm 2 does not invest. Firm 1 does not impose a technological tie, sets* $P_1 = \gamma_1 + z^M$*, sells systems to the entire market, and earns* $\pi_1 = [\bar{w} - \Gamma]M$ *. Firm 2 sets* $P_2 = w$ *and earns* $\pi_2 = 0$.

(iv) There are no other equilibria.

Proof. In any equilibrium, $z_i = z_1'$ satisfying $0 < z_i' < z^M$ is never a best response. Therefore, without loss of generality, we can restrict attention to $z_i \in \{0, z^M\}$. Consider Firm 1's incentives to impose a technological tie at stage two. If $w \geq \bar{w} - \Gamma$, Firm 1's (weakly) dominant strategy at stage two is not to impose a tie. Firm 1 has no incentive to tie if Firm 2 invests, and has no need to tie if Firm 1 invests (because Firm 2 would be foreclosed by $w \geq \bar{w} - \Gamma > \gamma_2$.) Thus there exist two equilibria with no tying for $w \geq \bar{w} - \Gamma$, corresponding to investment by Firm 2 or Firm 1. Furthermore, there exists an equilibrium in which Firm 1 imposes a tie, which has no cost and no consequence for payoffs. If $w < \bar{w} - \Gamma$, Firm 1 would impose a tie at stage two if Firm 2 invests. With a tie, Firm 1 would earn $\pi_1 = [\bar{w} - \Gamma]M > wM$. Therefore Firm 2 would not invest if $w < \bar{w} - \Gamma$. However, a tie is not necessary if Firm 2 does not invest and $w \geq \gamma_2$, because Firm 2 would be foreclosed by the component price. Thus, for $\gamma_2 \leq w < \bar{w} - \Gamma$, there is a unique equilibrium in which Firm 1 invests efficiently, Firm 2 does not invest, and Firm 1 does not impose a technological tie. The mere threat of a tie is sufficient to prevent Firm 2 from investing in this case. If $w < \gamma_2$, the component price does not foreclose Firm 2 from competing for system sales even if it does not invest. In this case, tying is a dominant strategy at stage two. Firm 2 would not invest and there is a unique equilibrium in which Firm 1 invests and imposes a technological tie. ■

5 Welfare comparisons

It is evident from Proposition 5 that consumer surplus is zero for all values of w in the technological tying game. Tying eliminates Firm 2 as a potential competitor when Firm 1 invests, and the high component price eliminates Firm 1 as a potential competitor when Firm 2 invests. Moreover, a comparison of Propositions 2 and 5 shows that technological tying eliminates any possibility of an efficient outcome in which Firm 2 serves the market when $w \leq \bar{w} - \Gamma$. Thus, technological tying reduces social welfare by enabling the less efficient Firm 1 to capture the market for systems. These observations lead to the conclusion that technological tying is unambiguously harmful to social and consumer welfare.

Corollary 6 *If $w < \gamma_1$, then consumer welfare is strictly lower in the technological tying game than in the basic product improvement game when either firm invests. If $w < \gamma_2$, then consumer surplus is strictly lower in the technological tying game than in the basic product improvement game when Firm 1 invests. Moreover, technological tying results in an inefficient market structure.*

6 Mixed strategies

The product improvement game does not possess pure strategy equilibria in which both firms invest. Moreover, firms' preferences over equilibria disagree. When $w < \bar{w} - \Gamma$, Firm 1 strictly prefers the inefficient pure strategy equilibrium in which it invests and forecloses Firm 2. Firm 2, of course, prefers the efficient equilibrium in which it captures the market. When the two firms disagree on a preferred pure strategy equilibrium, it is unclear how they could coordinate on which one to play. In the absence of effective coordination, mixed strategy equilibria in which both firms invest with some probability are more plausible. Moreover, a mixed strategy equilibrium has a realistic interpretation as rational conduct in a market environment in which firms are uncertain about each other's incentive for product improvement.

We examine mixed strategy equilibria in which each firm randomizes between a positive investment in product improvement and a zero investment. Thus it is possible for one or the other firm to invest alone, for neither to invest at all, or for both to invest. The investment incentives of each of the two firms depends on the probabilities of these different possible outcomes.

Suppose Firm 1 invests in product improvement $z_1 > 0$ with probability α, and Firm 2 invests $z_2 > 0$ with probability β. Assume provisionally that $\gamma_2 + z_2 > \gamma_1 + z_1 \geq \gamma_2$. These inequalities imply that Firm 2 wins the market if both firms invest and loses the market if Firm 1 invests alone, assuming Firm 2 is not foreclosed by a high wholesale price of component A ($\gamma_2 \geq w$). Clearly, unless $w > \gamma_2$, Firm 1 would not invest if $\gamma_2 > \gamma_1 + z_1$ because it would make no sales. We show below that $\gamma_2 + z_2 > \gamma_1 + z_1$ and that $\gamma_1 + z_1 \geq \gamma_2$ in a mixed strategy equilibrium.

Consider first the incentives of Firm 2. If Firm 2 does not invest in product improvement, then it makes sales only if Firm 1 does not invest and its expected profits are

$$\begin{aligned}\pi_2(0) &= (1-\alpha)\,\Gamma M \quad \text{if } w \leq \gamma_1 \\ &= (1-\alpha)\,(\gamma_2 - w)\,M \quad \text{if } \gamma_1 < w \leq \gamma_2 \\ &= 0 \quad \text{if } \gamma_2 < w.\end{aligned}$$

If Firm 2 improves its product by z_2, then its expected profits are

$$\begin{aligned}\pi_2(r_2) &= \alpha\,(\Gamma + z_2 - z_1)\,M + (1-\alpha)\,(z_2 + \Gamma)\,M - r\,(z_2) \quad \text{if } w \leq \gamma_1 \\ &= \alpha\,(\Gamma + z_2 - z_1)\,M + (1-\alpha)\,(\gamma_2 + z_2 - w)\,M \; - r\,(z_2) \quad \text{if } \gamma_1 < w \leq \gamma_1 + z_1 \\ &= (\gamma_2 + z_2 - w)\,M \; - r\,(z_2) \quad \text{if } \gamma_1 + z_1 < w \leq \gamma_2 + z_2.\end{aligned}$$

Conditional on investing, Firm 2's optimal product improvement is z^M for $w \leq \bar{w}$, which holds by assumption A4. Given Bertrand price competition at stage 2, Firm 2 fully internalizes the marginal returns from product improvement.

Now consider Firm 1's incentive for product improvement. Suppose Firm 2 invests in product improvement z^M with probability β. If Firm 1 does not invest, its expected profits are

$$\begin{aligned}\pi_1(0) &= wM \quad \text{if } w \leq \gamma_2 \\ &= \beta w M + (1-\beta)\gamma_1 M \quad \text{if } \gamma_2 < w \leq \bar{w} \\ &= \gamma_1 M \quad \text{if } \gamma_2 + z_2 < w.\end{aligned}$$

When $w \leq \gamma_2$, Firm 2 will sell systems whether or not it invests and Firm 1 will earn wM. When $\gamma_2 < w \leq \bar{w}$, Firm 2 can profitably sell only if it invests. If Firm 2 does not invest, Firm 1 will sell to all M customers at price γ_1.

Firm 1's expected profits when it invests are

$$\begin{aligned}\pi_1(z_1) &= wM + (1-\beta)\,(z_1 - \Gamma)\,M - r\,(z_1) \quad \text{if } w \leq \gamma_2 \\ &= \beta w M + (1-\beta)\,(\gamma_1 + z_1)\,M - r\,(z_1) \quad \text{if } \gamma_2 < w \leq \bar{w}.\end{aligned}$$

Conditional on investing, Firm 1's optimal product improvement is the solution to $(1-\beta)M = r'(z_1)$. Firm 1 invests less if it expects possible redundant investment by Firm 2; i.e., investment by Firm 1 "taxes" Firm 1's marginal incentive to invest. As discussed above, the converse is not true because of Firm 2's exogenous efficiency advantage. Thus $z_1 < z^M$ and $\gamma_1 + z_1 < \gamma_2 + z_2 \equiv \gamma_2 + z^M$, validating the provisional assumption made earlier.

We now examine the conditions for a mixed strategy equilibria. For a mixed strategy equilibrium to exist, Firm 2's expected profit must be the same whether or not it invests, and similarly for Firm 1. There are various cases.

- *Case 1*: $w \leq \gamma_1$. A mixed strategy equilibrium requires that both firms are indifferent to investing or not. Thus Firm 1 invests with probability α, where

$$\alpha = \frac{\pi^M}{(z_1 - \Gamma)M}$$

makes Firm 2 indifferent. Firm 2 invests with probability β, where

$$1 - \beta = \frac{r(z_1)}{(z_1 - \Gamma)M}$$

makes Firm 1 indifferent to investing. Note that a non-degenerate mixed strategy equilibrium requires $z_1 - \Gamma > 0$, which implies $\gamma_1 + z_1 > \gamma_2$ as assumed. Firm 1's product improvement z_1 is the solution to $(1-\beta)M = r'(z_1)$. Substituting the equilibrium condition for $(1-\beta)$ determines z_1^* satisfying

$$r'(z_1^*)(z_1^* - \Gamma) = r(z_1^*). \tag{4}$$

This equation has a unique positive solution z_1^* because $\pi^M > \Gamma M$ and $r(z)$ is convex.[14] The solution is increasing in Γ. Moreover, $z_1^* \to 0$ as $\Gamma \to 0$, and $z_1^* \to z^M$ as $\Gamma \to \frac{\pi^M}{M}$. Therefore z_1^* has a one-to-one relationship with Γ over the relevant range. Substituting z_1^* gives the equilibrium investment probabilities:

$$\alpha^* = \frac{r'(z_1^*)\,\pi^M}{r(z_1^*)\,M}$$

$$\beta^* = 1 - \frac{r'(z_1^*)}{M}.$$

It is straightforward to show that $\beta^* < 1$ and $\alpha^* > 0$. $\beta^* > 0$ is implied by equation (4) and assumption A3. $\alpha^* < 1$ if only if $r'(z_1^*)\,\pi^M < r(z_1^*)\,M$, which, therefore, is necessary for the existence of a mixed strategy equilibrium. This condition is satisfied if and only if $\pi^M < (z_1^* - \Gamma)\,M$.

[14] z_1^* is the solution to $z - \frac{r(z)}{r'(z)} = \Gamma$. The left-hand side is increasing in z and is equal to zero when $z = 0$ and $\pi^M/M \geq \Gamma$ when $z = z^M$. Thus there is a unique positive solution, z_1^*.

- *Case 2*: $\gamma_2 < w \leq \bar{w}$. Firm 2 is foreclosed if it does not invest. In this case, a mixed strategy equilibrium requires $1 - \beta = \frac{r(z_1)}{z_1 M}$, and Firm 1's marginal investment incentives imply $(1-\beta)M = r'(z_1)$. These two conditions are inconsistent with $z_1 > 0$ because $r(z)$ is everywhere convex. Thus a mixed strategy equilibrium does not exist in this case.

Proposition 7 *If and only if $w \leq \gamma_2$ and $\pi^M < (z_1^* - \Gamma) M$, then there exists a (nondegenerate) mixed strategy equilibrium in which Firm 1 chooses $z_1 = z_1^*$ with probability α^* and $z_1 = 0$ otherwise, and Firm 2 chooses $z_2 = z^M$ with probability β^* and $z_2 = 0$ otherwise.*

The conditions for the existence of a mixed strategy equilibrium are restrictive. Consider the following special case: $r(z) = \frac{b}{n} z^n$ with $n > 1$. In this case, $z^M = m^{\frac{1}{n-1}}$ and $\pi^M = b\frac{n-1}{n} m^{\frac{n}{n-1}}$, where $m = \frac{M}{b}$.[3] In a mixed strategy equilibrium, $z_1^* = \frac{n}{n-1}\Gamma$, $\alpha^* = (n-1)\frac{z^M}{z_1^*}$, and $\beta^* = 1 - \left(\frac{z_1^*}{z^M}\right)^{n-1}$. Necessary and sufficient conditions for a nondegenerate mixed strategy equilibrium in the power function case are $1 > \frac{z_1^*}{z^M} > n - 1 > 0$. Thus, a mixed strategy equilibrium does not exist if the R&D cost function is quadratic, but may exist in the power function case if the R&D cost function is less convex and $\Gamma$is not too large relative to m. To illustrate the restrictiveness of these conditions, suppose $\Gamma = 0.1$ and $m = 1$. Then a nondegenerate mixed strategy equilibrium requires $1.11 < n < 1.37$. If the power function is more or less convex than this, then a mixed strategy equilibrium fails to exist in this example.

If a mixed strategy equilibrium exists, then $\alpha^* > \beta^*$ if and only if

$$\pi^M > \frac{r(z_1^*)}{r'(z_1^*)} M - r(z_1^*).$$

This condition is satisfied because $\pi^M \geq z_1^* M - r(z_1^*)$ by Assumption 1 and convexity implies $z_1^* M - r(z_1^*) > \frac{r(z_1^*)}{r'(z_1^*)} M - r(z_1^*)$. Thus, we have

Corollary 8 *Firm 1 is more likely to invest than Firm 2 in a mixed strategy equilibrium.*

For a mixed strategy equilibrium to exist, Firm 1 has to invest with higher probability to keep both firms indifferent between investing and not investing in R&D, and therefore Firm 1 is more likely to win the market than Firm 2. In this sense, Firm 2's exogenous efficiency advantage translates into a strategic advantage for Firm 1 in a mixed strategy equilibrium.

Is welfare higher or lower in a mixed strategy equilibrium compared to a pure strategy equilibrium? Total welfare in a mixed strategy equilibrium is equal to

$$\begin{aligned} W_{mixed} &= \alpha^* (1 - \beta^*) [\gamma_1 M + \pi_1^*] \\ &\quad + (1 - \alpha^*) \beta^* \left[\gamma_2 M + \pi^M\right] \end{aligned}$$

$$
\begin{aligned}
&+\alpha^*\beta^*\left[\gamma_2 M + \pi^M - r(z_1^*)\right] \\
&+(1-\alpha^*)(1-\beta^*)\gamma_2 M.
\end{aligned}
$$

where $\pi_1^* = z_1^* M - r(z_1^*) < \pi^M$. The level of welfare in the efficient pure strategy equilibrium is $W_{pure_+} = \gamma_2 M + \pi^M$. Welfare is lower in a mixed strategy equilibrium compared to the efficient pure strategy equilibrium for three reasons. First, market structure is distorted because the less efficient Firm 1 sometimes wins the market in a mixed strategy equilibrium. Second, Firm 1 sometimes wastefully invests in product improvement because Firm 2 captures the entire market when both firms invest. Third, product improvement is deficient when both firms fail to invest.

The comparison with the inefficient pure strategy equilibrium is less clear on first inspection. The level of welfare in the inefficient pure strategy equilibrium is $W_{pure_-} = \gamma_1 M + \pi^M$. Therefore, the difference in welfare between the two equilibria is

$$
\begin{aligned}
W_{mixed} - W_{pure_-} = \; & \alpha^*(1-\beta^*)\left[\pi_1^* - \pi^M\right] \\
& +(1-\alpha^*)\beta^*\Gamma M \\
& +\alpha^*\beta^*\left[\Gamma M - r(z_1^*)\right] \\
& +(1-\alpha^*)(1-\beta^*)\left[\Gamma M - \pi^M\right].
\end{aligned}
$$

The first term is negative, because Firm 1 has deficient investment incentives in a mixed strategy equilibrium. The second term is positive because a mixed strategy equilibrium sometimes selects an efficient market structure. The third term is ambiguous because, even though Firm 2 is more efficient, Firm 1's investment in product improvement is wasteful. The fourth term is non-positive due to assumption A3 that Firm 1 can profitably leapfrog Firm 2. Thus, on the hand, the mixed strategy equilibrium sometimes beneficially achieves a more efficient market structure. On the other hand, a pure strategy equilibrium eliminates wasteful investment, eradicates the unfortunate possibility of no investments in product improvement, and improves the investment incentives of Firm 1. Thus if appears that welfare may be higher or lower in the mixed strategy equilibrium, depending on the strength of these various effects.[15]

Surprisingly, it is possible to resolve this ambiguity.

Proposition 9 *Welfare is lower in a mixed strategy equilibrium than in an inefficient pure strategy equilibrium.*

Proof. By rearranging terms, the welfare difference can be rewritten as:

$$
W_{mixed} - W_{pure_-} = \alpha^*\left[\pi_1^* - \pi^M\right]
$$

[15] Note that as $\Gamma \longrightarrow \frac{\pi^M}{M}$ from below, $z_1^* \longrightarrow z^M$, $\beta^* \longrightarrow 0$, and $\alpha^* \longrightarrow \frac{\Gamma}{(z^M - \Gamma)} < 1$, (as must be the case for a mixed strategy equilibrium to exist in the limit.) Therefore, in the limit, the welfare for the mixed strategy equilibrium is equal to that for the inefficient pure strategy equilibrium. The welfare ambiguity exists for $M\Gamma < \pi^M$.

$$
\begin{aligned}
&+\left(1-\alpha^*\right)\left[\Gamma M-\pi^M\right] \\
&+\alpha^*\beta^*\left[\left(\Gamma-z_1^*\right)M+\pi^M\right] \\
&+\left(1-\alpha^*\right)\beta^*\left[\pi^M\right].
\end{aligned}
$$

Using the definition $\alpha^* = \frac{\pi^M}{\left[z_1^*-\Gamma\right]M}$, the third term in this expression can be rewritten as

$$\alpha^*\beta^*\left[\left(\Gamma-z_1^*\right)M+\pi^M\right] = -\left(1-\alpha^*\right)\beta^*\pi^M.$$

This cancels with the fourth term, leaving

$$
\begin{aligned}
W_{mixed}-W_{pure\_} \quad = \quad & \alpha^*\left[\pi_1^*-\pi^M\right] \\
& +\left(1-\alpha^*\right)\left[\Gamma M-\pi^M\right],
\end{aligned}
$$

which is negative by assumption A3 and the definition of π^M. ∎

How do consumers fare in a mixed strategy equilibrium compared to a pure strategy equilibrium? There are two cases to consider.

- *Case 1*: $w \leq \gamma_1$. Expected consumer surplus (for each of the M consumers) is

  $$CS = \alpha^*\left(1-\beta^*\right)\Gamma+\alpha^*\beta^*z_1^*+\left(\gamma_1-w\right).$$

  Consumer surplus with mixed strategies is higher than in the efficient pure strategy equilibrium (which yields a consumer surplus of $\gamma_1 - w$). It may be higher or lower than in the inefficient pure strategy equilibrium (which yields $\gamma_2 - w$), depending on parameters.

- *Case 2*: $\gamma_1 < w \leq \gamma_2$. Expected consumer surplus (per consumer) is

  $$CS = \alpha^*\left(1-\beta^*\right)\Gamma+\alpha^*\beta^*z_1^*+\alpha(\gamma_1-w).$$

  This is clearly greater than the zero consumer surplus obtained in the efficient pure strategy equilibrium. Again it may be higher or lower than the positive level of surplus obtained in the inefficient pure strategy equilibrium, depending on parameters. The expected consumer surplus in a mixed strategy equilibrium is a decreasing function of the factor price w, because a higher w moderates the intensity of competition.

We are now in a position to reconsider the consequences of technological tying for social welfare. Recall that, in the technological tying game, if $w < \gamma_2$, then Firm 1 imposes a technological tie and forecloses Firm 2 from the systems market, leaving consumers with zero surplus. This is a unique equilibrium. In particular, there cannot be a mixed strategy equilibrium, because Firm 1 would always neutralize any product improvement by Firm 2 with a technological tie. Therefore, in this case, a technological tie eliminates any equilibrium in which Firm 2 imposes any competitive constraint on Firm 1 in the market for systems.

Corollary 10 *Technological tying increases social welfare relative to the mixed strategy equilibrium. Technological tying lowers consumer welfare.*

A mixed strategy is not an unrealistic description of firm behavior in the vertical differentiation model. Indeed, it is easy to "purify" the mixed strategy equilibrium[16] of the product improvement game as the limit of a Perfect Bayesian Equilibrium of a corresponding game of incomplete information in which the two firms are unsure of each other's incentive for product improvement.[17] The possibilities of wasteful investments in product improvement, deficient product improvement, or no investments at all, are all realistic outcomes when firms are unsure of each other's incentives and must make a prediction of what the other will do.

7 Conclusions

We have examined the causes and consequences of technological tying in a simple model of a market for systems. In this model, an upstream monopolist supplies an essential component to a competitor in the downstream systems market. The two firms compete on the price and quality for sales to consumers with homogeneous preferences over these vertically differentiated products. If the wholesale price of the essential component is sufficiently remunerative, then the upstream monopolist has no incentive to foreclose rival systems, either by selling only systems, contractually tying components, or designing an essential component so that it works better with its own systems. The equilibrium market structure is efficient in this case. Otherwise, the ability of the monopolist to impose a technological tie forecloses a more efficient provider of systems from gaining market share. Thus a technological tie, or even the mere threat of technological tie, can reduce social welfare by distorting market structure. In some cases, however, the ability of the vertically-integrated monopolist to impose a technological tie can increase social welfare by encouraging the firm to invest more in product improvement.

The ambiguity regarding the welfare effects of technological tying has to do with the nature of equilibrium were technological tying infeasible for the vertically-integrated firm, (say due to antitrust enforcement.) In some cases, a mixed strategy equilibrium can emerge when technological tying is infeasible. If the mixed strategy equilibrium is focal (i.e., if firms are unsure whether their rivals will invest), then the prevention of technological tying reduces social welfare under certain conditions. If instead an efficient pure strategy equilibrium

[16] See Harsanyi (1973).

[17] For example, assume that Firm 1's R&D cost function is $r(z_1) - \lambda u$, and Firm 2's is $r(z_2) - \lambda v$, with $\lambda > 0$. Assume further that u and v are privately known realizations of independent standard normal variables. With this modification, the product improvement game is transformed into a game of incomplete information. A Perfect Bayesian Equilibrium of this incomplete information game is characterized by cutoff values $\bar{u}$ and $\bar{v}$, such that Firm 1 invests z_1 if $u \leq \bar{u}$ and Firm 2 invests z_2 if $v \leq \bar{v}$. The respective probabilities of investment are $\alpha = \Phi(\bar{u})$ and $\beta = \Phi(\bar{v})$, where $\Phi(\cdot)$ is the standard normal cumulative distribution function. It is straightforward to prove that, as $\lambda \to 0$, $(z_1, z_2) \to \left(z_1^*, z^M\right)$ and $(\alpha, \beta) \to (\alpha^*, \beta^*)$. That is, the mixed strategy equilibrium of the basic product improvement game is a limit of Perfect Bayesian Equilibrium of a corresponding game of incomplete information as the significance of private information gets vanishingly small.

is focal, then preventing technological tying increases social welfare.

The simple vertical differentiation model does not admit pure strategy equilibria in which both firms invest in product improvement. In a companion paper, we allow for systems that are both vertically and horizontally product differentiated, so that some consumers prefer the system sold by Firm 1 and others prefer Firm 2's system, even when each has the same (vertical) quality and is sold at the same price. In this richer model, both firms may have an incentive to improve their products in a pure strategy equilibrium, and the ability of Firm 1 to technological tie might reduce Firm 2's market share short of complete foreclosure. The welfare effects of technological tying are more subtle in this case.

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